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Final Technical Report

Contract Number: N00014-86-K-0262
Title: Ductile Failure
Work Unit Number: 4324-771
Principal Investigator: A. Needleman Alan Needleman

Research Summary

Work under this contract has proceeded in three areas: (i) analyses of ductile fracture processes, with the aim of assessing the capability of analyses carried out within the Gurson constitutive framework for progressively cavitating solids to provide quantitative predictions of ductile fracture; (ii) the development of a finite element methodology for localization and failure analysis in order to carry out fully three dimensional finite element analyses of ductile failure processes and (iii) studies of the effects of fiber volume fraction, geometry and spacing on plastic response and ductile failure in metal matrix composites. (JES)

Analyses of Ductile Fracture Processes

A framework is used where the material's constitutive description allows for the possibility of a complete loss of stress carrying capacity, with the associated creation of new free surface, without any additional failure criterion being employed. Thus, fracture arises as a natural outcome of the deformation process. This contrasts with the usual approach to fracture analysis where the constitutive characterization of the material and a fracture criterion are specified separately. The major challenge here is the direct calculation of macroscopic ductility and toughness in terms of parameters characterizing measurable (and controllable) features of the material's microstructure. This framework is reviewed in [3].

In [5], void growth and ductile failure in the nonuniform multiaxial stress fields of notched bars were studied numerically and experimentally. U-notched bars with different notch acuities were made from partially consolidated and sintered iron powder compacts with various residual porosities. The matrix stress-strain relation and the initial void volume fractions used in the calculations were determined experimentally. The remaining parameters in the constitutive equations were evaluated from micromechanical models. Comparisons of the calculations with experimental results indicated that the constitutive model can provide good estimates of the evolution of the void volume fraction and of the strength reduction induced by void growth under a variety of nonuniform stress histories.

The experimental results in [5] also formed the basis for Becker's investigations [2] of non-uniform void volume fraction effects. The effects of the non-uniformity of the defect distribution were investigated by discretizing a volume of material. Based on experimental observations of porosity in sintered iron specimens, each subregion was assigned a defect density. Deformation of the region through the entire failure process is analyzed and the numerical results show the strong role played by the micro-inhomogeneity in limiting ductility. Little influence of the nonuniformity of the distribution on the stress-strain response was found, but a rather large effect of distribution on the strain to failure initiation.

The brittle-ductile transition for a high nitrogen steel was investigated in [6] by numerical analyses of the Charpy impact test. The material is described in terms of an elastic-viscoplastic constitutive model that accounts for the nucleation and growth of micro-voids, leading to ductile

fracture, as well as for cleavage failure by micro-crack nucleation. The temperature dependence of flow strength and strain hardening is included in the model, and this leads to the prediction of a transition from cleavage fracture to predominantly ductile fracture as the temperature increases. For the particular steel considered it is found that the variation of strain hardening with temperature has a strong effect on the failure mode transition. Both slow loading and impact loading of the Charpy specimen were analyzed. Most of the computations were based on a quasi-static formulation since, even at the strain rates encountered in the Charpy impact test, material strain rate sensitivity is the main time effect. The influence of material inertia was investigated in a few transient analyses.

In [7], crack growth along grain boundaries, by nucleation and growth of microvoids initiating from grain boundary particles, was studied experimentally and numerically using an elastic-viscoplastic constitutive model of a ductile porous solid to characterize the evolution of damage along the grain boundary. The material modelled was an Al-Li alloy with coarse grain boundary particles. Crack tip loading conditions were obtained by modelling the complete compact tensile specimen geometry used in the experiments. The distribution of grain boundary voids was modelled by allowing void nucleation in a band, the width of which is the grain boundary particle spacing. The grains were modelled as roughly circular regions free of void nucleating particles. The grain size and width of the grain boundary void nucleating band were varied to determine their influence on fracture initiation and toughness predictions. The predicted values of K_{IC} and tearing modulus, based on calculated J-resistance curves, were found to be in reasonable agreement with experimentally determined values. The calculations show a strong dependence of the fracture toughness on the width of the grain boundary void nucleating band and a mild dependence on the grain size.

Analyses of ductile crack growth were discussed in [10] where the material's constitutive description allows for the possibility of a complete loss of stress carrying capacity, with the associated creation of new free surface. No additional failure criterion is employed so that fracture arises as a natural outcome of the deformation process. Attention is confined to circumstances where the microscale fracture mechanism is ductile void growth. The overall aim is the prediction of parameters characterizing macroscopic toughness, e.g. J_{Ic} and the tearing modulus, in terms of properties describing the fracture mechanism operating on the microscale, e.g. the density and spacing of void nucleating particles. Representative results were presented and some of the numerical challenges raised by this sort of analysis were discussed.

In [14], dynamic crack growth was analyzed numerically for a plane strain double edge cracked specimen subject to symmetric impulsive tensile loading at the two ends. The material behavior is described in terms of an elastic-viscoplastic constitutive model that accounts for ductile fracture by the nucleation and subsequent growth of voids to coalescence. Two populations of second phase particles are represented, including large inclusions or inclusion colonies with low strength, which result in large voids near the crack tip at an early stage, and small second phase particles, which require large strains before cavities nucleate. The crack growth velocities determined were entirely based on the ductile failure predictions of the material model, and thus this study is free from ad hoc assumptions regarding appropriate dynamic crack growth criteria. Adiabatic heating due to plastic dissipation and the resulting thermal softening were accounted for in the analyses. Different prescribed impact velocities, inclusion spacings and values of the inclusion nucleation stress were considered. Predictions for the dynamic crack growth behavior and for the time variation of crack tip characterizing parameters were obtained for each case analyzed.

Finite Element Analysis of Localized Plastic Flow

The poor performance of conventional isoparametric elements in the presence of localization can be attributed to an inadequate representation of the deformation field within the element. Ideally, an element overlapping with a shear band interface should be capable of developing strain discontinuities to be able to conform to the prevailing mode of deformation. However, the local strain field of an isoparametric element is smooth and cannot accommodate strain discontinuities of arbitrary orientation. As a result, the computed shear band is overly diffuse. A remedy which naturally suggests itself is to enrich the local strain representation so as to render the element more conducive to localization, in the spirit of assumed strain methods. Perspectives on this framework are given in [4] and [9].

In [12], the finite element method for localization analysis of Ortiz *et al.*, *Comp. Meth. Appl. Mech. Engng.*, **61**, 189, 1987, was generalized to account for finite deformations and for material rate dependence. Special shape functions are added to the finite element basis to reproduce band-like localized deformation modes. The amplitudes of these additional modes are eliminated locally by static condensation. The performance of the enhanced element was illustrated in a problem involving shear localization in a plane strain tensile bar. Solutions based on the enhanced element were compared with corresponding results obtained from the underlying compatible isoparametric quadrilateral element and from crossed-triangular and uniformly reduced integration elements. In the finite deformation context, the enhanced element solution is not very sensitive to the precise specification of initial orientation of the additional band-like modes. The enhanced element formulation can be used for a broad range of rate independent and rate dependent material behaviors in two dimensional and three dimensional problems.

Micromechanical Modelling of Deformation and Failure in Metal Matrix Composites

With recent advances in processing technology, the ability to produce, in economically feasible quantities, a wide range of metal-matrix composites is increasing dramatically. Discontinuously reinforced metal-matrix composites constitute a large portion of these advanced materials that are both machinable and workable using conventional processing techniques. The manufacturing of these materials can easily be scaled up to production quantities. The low ductility exhibited by discontinuously-reinforced metal-matrix composites is the primary obstacle preventing their introduction into many structural applications. Yet the influence of controlled matrix microstructural variations on the strain-to-failure of whisker-reinforced metal-matrix composites remains poorly understood. Work in this area has been aimed at obtaining a better understanding of the deformation and failure mechanisms in these materials.

In [1] a description of the process of void nucleation at whisker ends was developed that is both quantitative and predictive. Comparisons were presented between predicted and observed modes of failure initiation in reinforced aluminum composites. Experimental observations were made by transmission electron microscopy (TEM) of deformation microstructures immediately beneath tensile fracture surfaces and the analyses were based on a continuum model for void nucleation by interface decohesion introduced in Needleman, *J. Appl. Mech.*, **54**, 525, 1987.

In [11], the effects of fiber spacing and fiber volume fraction on void nucleation in short-fiber composites were investigated through calculations based on this continuum model for interface decohesion. Using material parameters that simulate Al-SiC short-fiber composites, it was found that the stress and strain levels at which debonding occurs is strongly dependent on fiber spacing and volume fraction. In addition, fiber spacing also affects the mode of debonding at fiber ends.

The results provide insight into the effects of controllable microstructural parameters on damage mechanisms that ultimately cause composite failure.

In [8], finite element method predictions were obtained for uniaxial loading of perfectly aligned fibers that were qualitatively in agreement with experimental results. The finite element model correctly predicted that the yield strength of the composite material is independent of matrix variations due to aging state and that the strain-hardening exponent of the composite is quite different from that of the unreinforced material. Quantitatively, however, finite element predictions for stress-strain response were not within acceptable bounds of the experimental results. The calculations also revealed the important role of the hydrostatic tension induced by constrained plastic flow in the hardening process.

The deformation characteristics of ceramic whisker- and particulate-reinforced metal-matrix composites were studied experimentally and numerically in [13] with the objective of investigating the dependence of tensile properties on the matrix microstructure and on the size, shape, and distribution of the reinforcement phase. The model systems chosen for comparison with the numerical simulations included SiC whisker-reinforced 2124 aluminum alloys with well-characterized microstructures and 1100-o aluminum reinforced with different amounts of SiC particulates. The overall constitutive response of the composite and the evolution of stress and strain field quantities in the matrix of the composite were computed using finite element models within the context of axisymmetric and plane strain unit cell formulations. The results indicate that the development of significant triaxial stresses within the composite matrix, due to the constraint imposed by the reinforcements, provides an important contribution to strengthening. Systematic calculations of the alterations in matrix field quantities in response to controlled changes in reinforcement distribution give valuable insights into the effects of *particle clustering* on the tensile properties. The numerical results also deliver a mechanistic rationale for experimentally observed trends on: (i) the effects of reinforcement morphology and volume fraction on yield and strain hardening behavior of the composite, (ii) the pronounced influence of reinforcement clustering on the overall constitutive response, (iii) ductile failure by void growth within the composite matrix, (iv) the insensitivity of the yield strength of the composite to changes in matrix microstructure, and (v) the dependence of ductility on the microstructure of the matrix and on the morphology and distribution of the reinforcement. The predictions of the analyses were compared and contrasted with current theories of elastic and plastic response in multi-phase materials in an attempt to develop an overall perspective on the mechanisms of composite strengthening and of matrix and interfacial failure.

List of Publications

[1] S.R. Nutt and A. Needleman, "Void Nucleation at Fiber Ends in Al-SiC Composites," *Scripta Metallurgica*, **21**, 705-710, (1987).

[2] R. Becker, "The Effect of Porosity Distribution on Failure," *Journal of the Mechanics and Physics of Solids*, **35**, 577-599 (1987).

[3] A. Needleman and R. Becker, "Analyses of Ductile Failure Processes," *Interdisciplinary Issues in Materials Processing and Manufacturing*, edited by S.K. Samanta et al., ASME, Volume 1, pp. 139-161, (1987).

[4] Y. Leroy, A. Nacar, A. Needleman and M. Ortiz, "A Finite Element Method for Localization Analysis," *Advances in Inelastic Analysis*, edited by S. Nakazawa, K. Willam and N. Rebelo, ASME, AMD Volume 88, pp. 97-106 (1987).

[5] R. Becker, A. Needleman, O. Richmond and V. Tvergaard, "Void Growth and Failure in Notched Bars," *Journal of the Mechanics and Physics of Solids*, **36**, 317-351 (1988).

[6] V. Tvergaard and A. Needleman, "An Analysis of the Temperature and Rate Dependence of Charpy V-Notch Energies for a High Nitrogen Steel," *International Journal of Fracture*, **37**, 197-215 (1988).

[7] R. Becker, A. Needleman, S. Suresh, V. Tvergaard and A.K.Vasudevan, "An Analysis of Ductile Failure by Grain Boundary Void Growth," *Acta Metallurgica*, **37**, 99-120 (1989).

[8] T. Christman, A. Needleman, S.R. Nutt and S. Suresh, "On Microstructural Evolution and Micromechanical Modelling of Deformation of a Whisker-Reinforced Metal-Matrix Composite," *Materials Science and Engineering*, **107A**, 49-61 (1989).

[9] Y. Leroy, A. Needleman and M. Ortiz, "An Overview of Finite Element Methods for the Analysis of Strain Localization," in *Cracking and Damage: Strain Localization and Size Effect*, (ed. by J. Mazars and Z.P. Bazant), Elsevier Applied Science, 269-294 (1989).

[10] A. Needleman and V. Tvergaard, "Analyses of Crack Growth in Ductile Solids," in *Proceedings of the 7th International Conference on Fracture*, (ed. by K. Salama *et al.*), Pergamon Press, 2041-2048 (1989).

[11] A. Needleman and S. R. Nutt, "Void Formation in Short-Fiber Composites," in *Proceedings of the 7th International Conference on Fracture*, (ed. by K. Salama *et al.*), Pergamon Press, 2211-2218 (1989).

[12] A. Nacar, A. Needleman and M. Ortiz, "A Finite Element Method for Analyzing Localization in Rate Dependent Solids at Finite Strains," *Computer Methods in Applied Mechanics and Engineering*, to be published.

[13] T. Christman, A. Needleman and S. Suresh, "An Experimental and Numerical Study of Deformation in Metal-Ceramic Composites," *Acta Metallurgica*, to be published.

[14] A. Needleman and V. Tvergaard, "An Analysis of Dynamic, Ductile Crack Growth in a Double Edge Cracked Specimen," submitted for publication.